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## STELLAR VARIABILITY IN THE METAL-RICH, OBSCURED GLOBULAR CLUSTER TERZAN 5<sup>1</sup>

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### ABSTRACT

We present the results of a search for variability in and near the core of the metal-rich, obscured globular cluster Terzan 5, using the near-infrared camera and multiobject spectrometer (NICMOS) on board the *Hubble Space Telescope*. This extreme cluster has approximately solar metallicity and a central density that places it in the upper few percent of all clusters. It is estimated to have the highest interaction rate of any galactic globular cluster. The large extinction toward Terzan 5 and the severe stellar crowding near the cluster center present a substantial observational challenge. Using time-series analysis, we discovered two variable stars in this cluster. The first is an RRab Lyrae variable with a period of  $\sim 0.61$  days, a longer period than that of field stars with similar high metallicities. This period is shorter, however, than the average periods of RR Lyraes found in the metal-rich globular clusters NGC 6441, NGC 6388, and 47 Tuc. The second variable is a blue star with a 7 hr period sinusoidal variation and a likely orbital period of 14 hr. This star is probably an eclipsing blue straggler or (less likely) the infrared counterpart to the low-mass X-ray binary known in Terzan 5. Because of the extreme crowding and overlapping Airy profile of the IR point-spread function, we fall short of our original goal of detecting cataclysmic variables via Pax emission and detecting variable infrared emission from the location of the binary millisecond pulsar in Terzan 5.

*Subject headings:* globular clusters: general — infrared: general — stars: variables: other

### 1. INTRODUCTION

The study of variable stars in globular clusters has a long, rich history. Studies of RR Lyrae variables, long-period variables, and Population II Cepheids have addressed fundamental questions about stellar evolution, globular-cluster evolution, and the distance scale. More recently, observations of variable stars such as millisecond pulsars (MSPs), cataclysmic variables (CVs), and eclipsing binaries have been motivated by studies of stellar interactions and globular-cluster dynamics. For example, during stellar encounters, binaries are expected to become more tightly bound and give the energy difference up to passing stars, a process that can support a cluster against core collapse.

Observations with the *Hubble Space Telescope* (*HST*) have been crucial in overcoming the significant crowding present in such dense stellar environments. For example, *HST* observations of the center of the massive globular cluster 47 Tucanae have discovered two likely CVs (Paresce & De Marchi 1994; Shara et al. 1996), nine eclipsing binaries (Edmonds et al. 1996), and six pulsating blue stragglers (BSs; Gilliland et al. 1998). Observations of the collapsed-core cluster NGC 6397 have revealed five CVs (Cool et al. 1995; Grindlay et al. 1995; Edmonds et al. 1999; Grindlay 1999) and three likely low-mass white dwarfs (WDs; Cool et al. 1998; Edmonds et al. 1999) that may also be MSPs.

*HST* has also been used to obtain the first high-quality images and color-magnitude diagrams (CMDs) of NGC 6441 and NGC 6388, two partially obscured clusters with

surprisingly rich blue horizontal branches (HBs) when their high metallicity is taken into account (Rich et al. 1997). Most metal-rich clusters have red, stubby HBs, in agreement with standard theories of stellar evolution. As metallicity decreases HBs usually become increasingly blue, but some clusters, such as NGC 6441 and NGC 6388, contradict this pattern, and a second parameter is assumed to affect HB morphology. The cause of this “second parameter effect” is a subject of vigorous debate, but some intriguing clues have appeared. Both NGC 6441 and NGC 6388 appear to have HBs that are brighter than the HBs in metal-poor clusters. Variability searches in these clusters have shown subsequently that the RR Lyrae stars have significantly longer periods than expected for metal-rich stars (Layden et al. 1999; Pritzl et al. 2000), as does the RR Lyrae V9 in 47 Tuc (Carney, Storm, & Williams 1993). This apparently new subclass of long-period, metal-rich RR Lyraes may show the lack of universality of the luminosity-metallicity relation for RR Lyraes and may require the establishment of a third Oosterhoff group (Pritzl et al. 2000).

The globular cluster Terzan 5, the subject of this paper, represents an excellent laboratory for the studies introduced above. Because its metallicity is close to solar (Ortolani, Barbuy, & Bica 1996; Cohn et al. 2000), it is ideal for studies of HB morphology and RR Lyrae behavior in a metal-rich globular cluster. It also has the highest predicted rate of stellar collisions of any galactic globular cluster (Verbunt & Hut 1987) making it a laboratory for stellar dynamics. It is already known to contain a low-mass X-ray binary (LMXB) (Johnston, Verbunt, & Hasinger 1995), a binary MSP (Lyne et al. 1990; Nice & Thorsett 1992), one other pulsar, and a large number of unresolved pulsars (Fruchter & Goss 2000). Unfortunately, Terzan 5 is highly reddened, with

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$E(B-V) = 2.49$  (Ortolani et al. 1996), and because of its large mass, the crowding near cluster center, where the binaries are expected to be concentrated, is a formidable problem.

Here we describe an attempt to overcome the high reddening and crowding in Terzan 5 by observing it in the IR with the near-infrared camera and multiobject spectrometer (NICMOS) on board *HST*. Our aims were (1) to search the center of the cluster for CVs and the IR counterpart of the LMXB using wide (F187W) and narrowband (F187N) NICMOS filters centered on Pa $\alpha$  and (2) to search for variability from the binary MSP. The general photometric results are described in Cohn et al. (2000). In this paper we describe a detailed search for variability in two fields, one covering the center of the cluster and another containing the binary MSP. Although we fall short of detecting CVs because of crowding and no evidence is found for variability of any of the objects lying in the error circle of the MSP, we do detect an interesting RR Lyrae variable and a second variable that is likely to be an eclipsing BS or (less likely) the IR counterpart of the LMXB.

## 2. OBSERVATIONS AND ANALYSIS

### 2.1. Data Reduction

The Terzan 5 NICMOS observations described here were obtained on 1998 June 2 and 3. Two pointings of four orbits each were obtained. Pointing 1 directed the NIC2 camera ( $19''.2 \times 19''.2$  field of view [FOV]) at the center of the cluster, and pointing 2 directed the NIC1 camera ( $11''.5 \times 11''.5$  FOV) at the eclipsing MSP. Pointing 1 was adopted for  $\sim 75\%$  of each orbit, and the telescope then slewed to pointing 2 for the remainder of each orbit. All three NICMOS cameras were used in parallel for these observations, but only the NIC2 data for pointing 1 and the NIC1 data for pointing 2 are of interest and are described here.

Within pointing 1 a dither pattern was adopted with different pointing positions for each of the eight orbits. The pattern consisted of eight of nine points of a  $6 \times 6$  pixel square dither, with three pixel steps. Superimposed on this box pattern were subpixel offsets in one-eighth pixel steps. Both of these factors were designed to improve the quality of the photometry at the expense of the quality of the time series. The box pattern corrects the photometry for image defects such as bad pixels and flat-field errors, and the subpixel offsets improve the effective sampling of the images for better resolution. For the MSP pointing, no dithering was used to maximize the time-series quality, but a different field position was used for the second set of four orbits to guard against accidental positioning on a bad pixel.

For the central NIC2 observations, F110W, F187W, and F187N were used for each of the eight orbits. The F187W and F187N filters are the infrared analogs of *R* and *H $\alpha$* , respectively, and the F110W filter is similar to *J*. The latter was included to give color information for the observed stars. For the NIC1/MSP field, only F140W images were obtained. This filter was chosen because it gave the highest signal-to-noise ratio (S/N) and the greatest chance of detecting variability from the MSP, in particular, evidence of orbital variability from the secondary, as in the system PSR 1957+20 (Djorgovski & Evans 1988; Callanan, van Paradijs, & Rengelink 1995). For the remainder of this

section we will discuss only the central NIC2 observations.

The NICMOS data were obtained in MULTIACCUM mode, which provides intermediate, nondestructive readouts during a single observation. For the F110W and F187W filters, the “STEP32” sequence was used with 17 or 18 samples. The readout times were 0.3, 0.6, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0, 64.0 s, etc. (the remaining times in 32.0 s steps). For the F187N filter, the “STEP128” sequence was used with the same readout times as above except extending up to 128 s readouts (with 22 samples). Standard processing was applied via the STScI pipeline. Here a problem was discovered with the processed F187N images with a large number of stars found to contain pixels with unusually small signal levels. With guidance from M. Dickinson, T. Boecker, and H. Bushouse at STScI, it was discovered that the saturation thresholds for the F187N processing were set incorrectly. Lowering the saturation thresholds by 5%–10% and reprocessing using CALNICA repaired almost 100% of these faulty pixels.

Customized software was used to convert the accumulated data into individual exposures suitable for time-series analysis. The data quality files were used to remove cosmic rays and to avoid using saturated pixels. After blinking the individual images, pixels affected by “grot” (probably small flecks of paint) were flagged as bad pixels, and the bad pixel list was updated. Single bad pixels were corrected or “cleaned” by adopting the average of the four adjacent pixels, but no attempt was made to correct groups of two or more adjacent bad pixels.

### 2.2. Time-Series Analysis

Our star list for differential photometry was based on the work of Cohn et al. (2000) who averaged and combined the eight separate images for each filter into single, oversampled images using the STSDAS drizzle routine. The F110W filter, which gave the deepest, best-resolved final image, was used to calculate the master star list used here (containing 3091 stars).

The following two standard photometry techniques were used to produce time series:

1. *Aperture photometry*.—A plate solution determined from a sample of bright stars was applied at each time to calculate the coordinate shifts to be applied to the master coordinate list. Aperture photometry was then carried out using DAOPHOT under IRAF, with an aperture radius of 2.5 pixels, roughly matching the radius of the first Airy minima for the F187 data. To improve the S/N of the intensity measurements and minimize the contribution from near neighbors, the signal in each pixel in each aperture was weighted by a simple model of the point-spread function (PSF). Sky values were determined from the mode of the counts in an annulus around each star.

2. *PSF fitting*.—The extreme crowding of the central Terzan 5 field, especially the large number of bright giants, the complicated nature and large radial extent of the PSF, and the marginal sampling of the individual images, caused problems with PSF fitting for the faintest stars. In particular, many faint objects in the master star list were not detected in the F110W images (the most undersampled data) using ALLSTAR. Therefore, we experimented with a smaller sized list of 1702 stars containing objects found in PSF fitting of both the F110W and F187W images (Cohn et al. 2000).

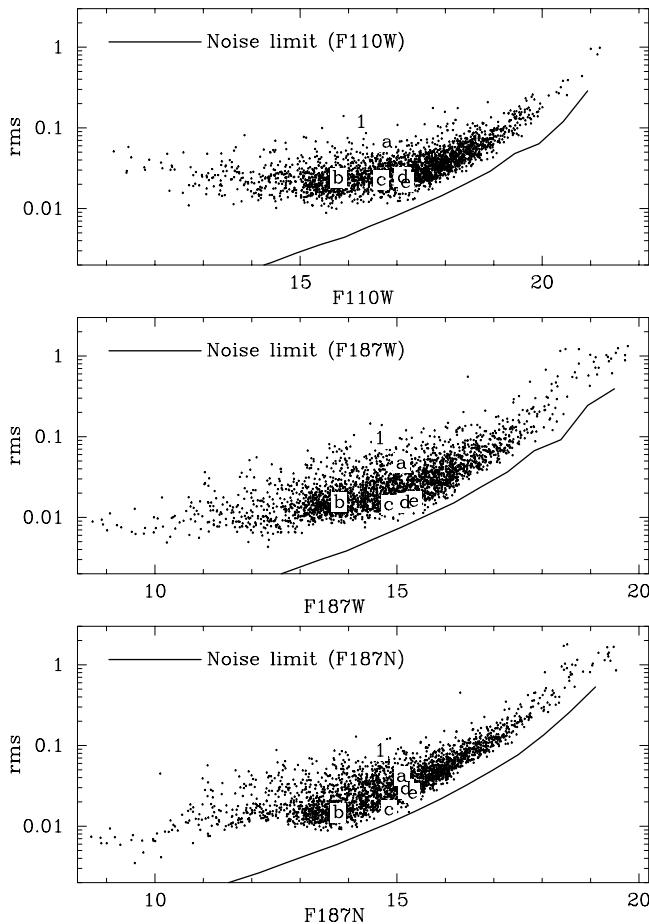


FIG. 1.—Plots of rms vs. magnitude for the three different NIC2 filters used. The solid line shows the Poisson limits for aperture photometry. The symbols represent the variable V1 (1) and its near neighbors (a–e).

We examined the counts for each star as a function of time for the longest readout times (32 or 128 s) and found a high correlation between the time series of different stars with a linear falloff in the counts as a function of time during an exposure caused, we believe, by “persistence”

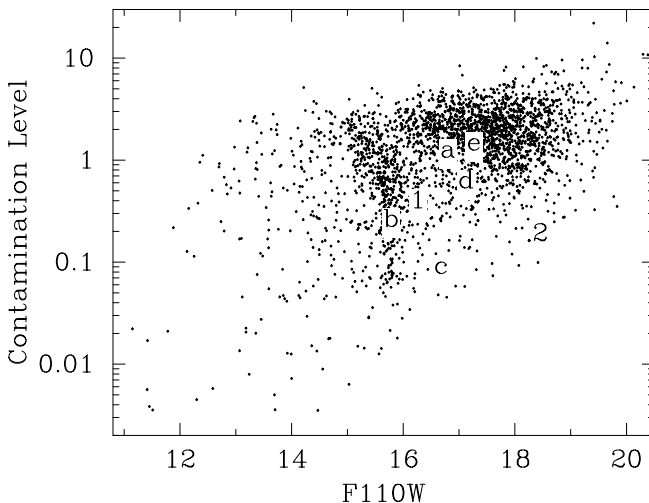


FIG. 2.—Contamination level plotted against F110W. The same symbols as Fig. 1 are used, except we also include the variable V2 (2).

(Skinner et al. 1998). To remove this artifact, we calculated the average time series for bright nonsaturated stars and normalized each time series by this average function. Zero points based on the photometry of Cohn et al. (2000) were used.

We then compared the two photometry techniques using the root mean square (rms) values calculated for each star. Only the exposures with the longest sample times (either 32 or 128 s) were included in this calculation. Aperture photometry gave significantly better results than PSF fitting for the F110W data and comparable or slightly better results for the F187W and F187N data. Since the aperture photometry results were superior, we will quote them unless otherwise noted.

Figure 1 shows plots of rms versus F110W, F187W, and F187N magnitudes. The solid line shows the theoretical rms based on the limits from photon noise and readout noise (Kjeldsen & Frandsen 1992). We have plotted the average rms limit in 0.5 mag wide bins in each case. At faint magnitudes our measured rms values are only factors of 2–3 above the Poisson limit, a reasonable result given the large amount of dithering adopted and other systematic effects.

Because the images are crowded, we have examined the degree of overlap between stars. We define the “contamination” level (CL) for any star to be the amount of light from other stars falling within its aperture (for example, CL = 0 implies a star is completely isolated and CL = 1 implies equal contribution from the star and neighbors). The CLs for the F110W filter are shown in Figure 2. The median CL is 1.70, showing the high level of crowding in the data.

To search for variables, we concentrated on time-series analysis. We placed the stars in order of decreasing brightness, divided the stars into bins containing 50 stars, and searched for stars with unusually large rms values in each bin using an iterative procedure. Candidate variables were identified as having unusually large ( $> 3\sigma$ ) rms values in all three of the filters.

### 3. RESULTS

#### 3.1. Detected Variables

Thirteen candidate variables were discovered using the above method. All but three of these stars have CL  $> 2.0$  in the F110W image. The second most isolated candidate variable (at 194.05, 197.78 in orbit 1 coordinates) has CL = 0.37 and is clearly a good candidate variable. This star will be referred to as V1 and is located at  $\alpha(2000) = 17^{\text{h}}48^{\text{m}}05^{\text{s}}.14$ ,  $\delta(2000) = -24^{\circ}46'38''.2$ . Figure 1 shows V1 along with stars lying within 12 pixels of V1 (a–e). Star a is a faint star lying only 2.1 pixels from V1. The overlapping PSF of the variable imposes an apparent but false signal for its fainter companion. None of the other stars have convincing variations. Further discussion of V1 will be given in § 3.2.

A deeper search also was carried out for  $2\sigma$  variations. This resulted in 90 variable candidates with 13 stars having CL  $< 2.0$ , but this deeper study revealed only one new, believable variable, henceforth V2 (see § 3.3), located at  $\alpha(2000) = 17^{\text{h}}48^{\text{m}}05^{\text{s}}.06$ ,  $\delta(2000) = -24^{\circ}46'52''.5$ . A finding chart (Fig. 3) shows the F110W NIC2 image from the first orbit and the positions of V1 and V2. The summed image from the first orbit is shown (rather than the dithered, over-sampled image) to show the level of crowding in the single orbit images.

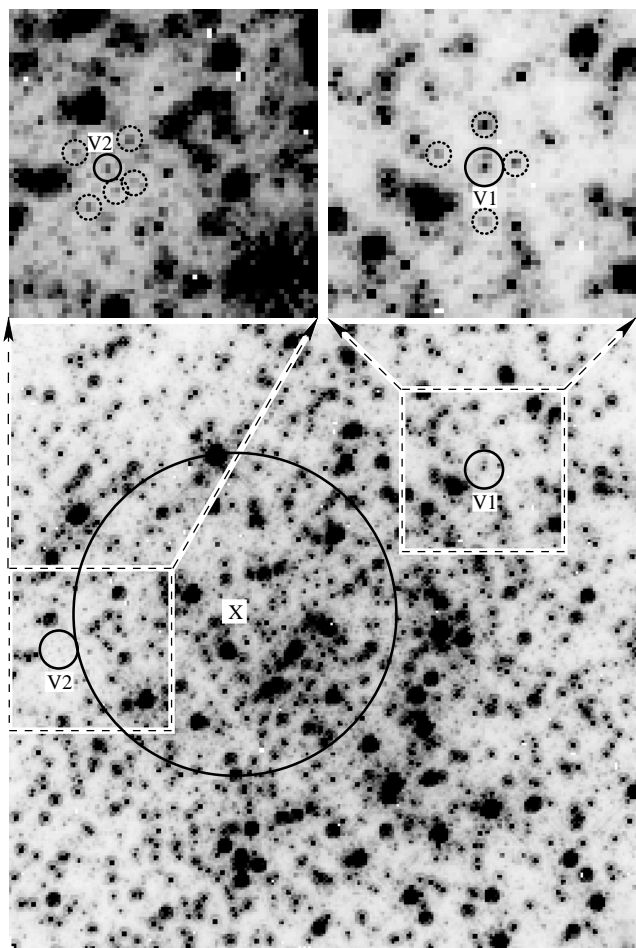


FIG. 3.—F110W image for the first orbit, including the positions of V1 and V2 and the position and error circle of the X-ray source from Johnston et al. (1995). The close-up figures include filled circles for the variables and dotted circles for the near neighbors of V1 (*b–e*; *a* is not circled and is found 2 pixels above V1) and V2.

To test the completeness and depth of our variable search, we carried out time-series simulations of our F110W data, the least crowded images. We calculated aperture-photometry time series for a grid of positions and added sinusoids with an amplitude of 0.3 mag to these time series. We considered a fake variable to be “detected” if the rms was more than twice the rms without adding in the sinusoid. This technique automatically takes crowding into account. We then tested detection efficiency as a function of radial distance and absolute magnitude of the fake variables (for periods between 0.5 and 15 hr, the detection efficiency is constant to within a few percent). The  $M_V$  calibration was based on the assumption that the simulated stars belong to the main sequence or the giant branch, using stellar isochrones (see § 3.2.1). The percentage of detected 0.3 mag simulations as a function of radial distance from the center of the cluster is shown in Figure 4. Note the dramatic improvement in detection efficiency as one moves away from the center of the cluster but the lack of sensitivity to variables with  $M_V > 4$  (just above the main-sequence turn-off [MSTO]).

Variable searches were also attempted using analysis of the Lomb-Scargle periodogram (Scargle 1982) of each time series. However, the eight orbits were spread out over  $\sim 1.3$

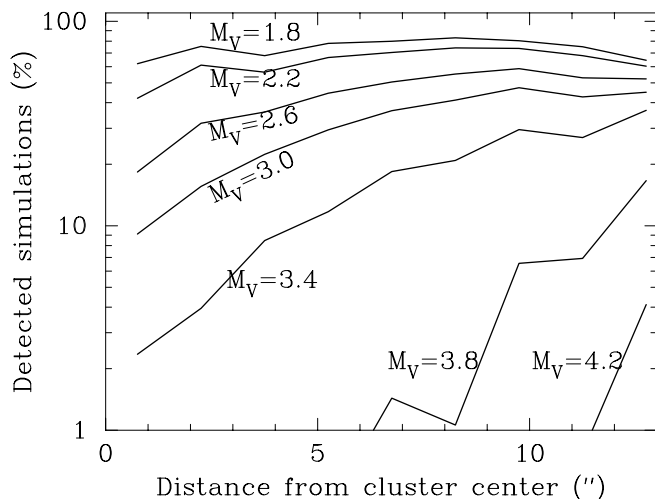


FIG. 4.—Percentage of detected simulations (with 0.3 mag amplitude) as a function of radial distance from the center of the cluster. A range of absolute magnitudes was used for the simulations. The drop in detection rate beyond a radial distance of  $\sim 10''$  is because of the decreased fraction of annulus that lies in the NIC2 field.

days, and the noise from orbit to orbit is larger than the noise within a single orbit because of the dithering. Therefore, many false signals with periods of a few hours were found in the power spectra, and this method proved to be less efficient at finding candidate variables than working in the time domain.

### 3.2. V1: RR Lyrae Variable

We applied several extra tests to V1 to confirm its variability. Because a bad pixel at (197, 203) falls within the V1 aperture for the fourth and fifth dither positions (1.2 and 1.5 pixels away, respectively), we verified that there is no clear drop in the flux for these two dither positions. Besides these two dither positions, the average offset of the bad pixel from V1 is 3.9 pixels, well outside our aperture. As a second test we placed a grid around V1 and calculated time series for apertures centered on this grid. Variability was only found for apertures within a few pixels of V1. Finally, we verified that V1’s light curve from PSF fitting was similar to that for aperture photometry and that the quality of the fits was reasonable compared to other stars.

Henceforth we consider V1 to be a true variable. We now discuss the photometry and time series for this star.

#### 3.2.1. Photometry

Figure 5 shows the F110W versus F110W – F187W CMD for the central NIC2 field from Cohn et al. (2000). The labels represent the variable V1 and its near neighbors (*a–e*). The variable is clearly a blue star, while the stars labeled with asterisks are other possible blue stars, many of which are likely to be red giants scattered into the blue region of the CMD by errors. The solid line shows the stellar isochrones of Bergbusch & Vandenberg (1992). We extrapolated the highest metallicity stellar isochrones ( $\text{Fe}/\text{H} = -0.47$ ) to solar metallicity, fed the  $T_{\text{eff}}$  and  $\log g$  values into Kurucz atmospheres, and used SYNPHOT to estimate the NICMOS magnitudes of these Kurucz models, using the reddening measured by Cohn et al. (2000). Besides the main sequence and giant branch, we also show simple models of the HB, assuming a large spread in effective tem-

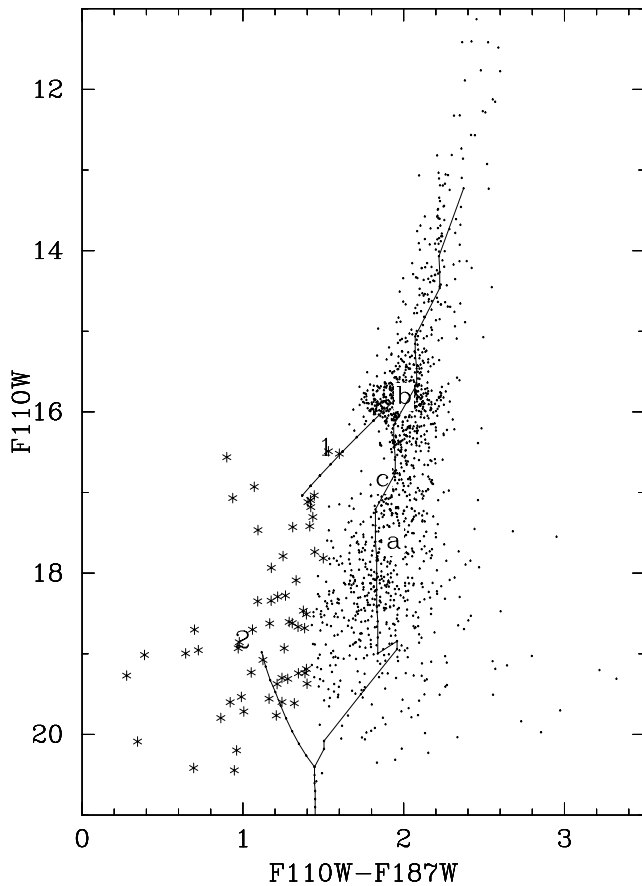


FIG. 5.—F110W vs. F110W - F187W CMD from Cohn et al. (2000). The numbered and labeled stars discussed in the text are shown along with a selection of blue stars (*asterisks*). Isochrones from Bergbusch & Vandenberg (1992) are shown by the solid line plus HB and BS sequences. The jagged appearance of the isochrones is because they have been fed through Kurucz atmospheres, quantified in  $T_{\text{eff}}$  and  $\log g$ , to calculate the NICMOS magnitudes.

perature. Since the variable lies close to an extension of the HB, an RR Lyrae source for the variations is suggested. We also show a model BS sequence (guided by  $T_{\text{eff}}$  and  $\log g$  values from Shara, Saffer, & Livio 1997 for a bright BS in 47 Tuc). Our BS sequence extends to  $\sim 2.2$  mag above the MSTO in an unreddened  $V$  versus  $B - V$  CMD, about equal to the extent of the BS sequence in the center of 47 Tuc obtained with *HST* (Gilliland et al. 1998).

Despite the very small FOV of the NIC2 camera, there is some field-star contamination because the line of sight toward Terzan 5 is close to the galactic center ( $L = 3.81$ ,  $B = 1.67$ ). We estimated the field-star component using the ground-based observations of Ortolani et al. (1996). Using their SUSI ( $2.2 \times 2.2$  FOV) observations extending to about 1.5 mag below the HB (see their Fig. 5), we defined field stars to have  $V - I < 3.2$ . Scaling to the NIC2 FOV, we predict four to five bright field stars should be found in our field. This is in excellent agreement with Figure 5 showing five to six likely field stars with  $F110W < 19.0$  and  $F110W - F187W < -0.8$ .

### 3.2.2. Time Series

Figure 6 shows the aperture photometry light curves of V1 along with light curves of stars *a*–*e*. The F187W and F187N light curves have been shifted vertically so that the apparent peaks of the light curves (in orbit 3) match up.

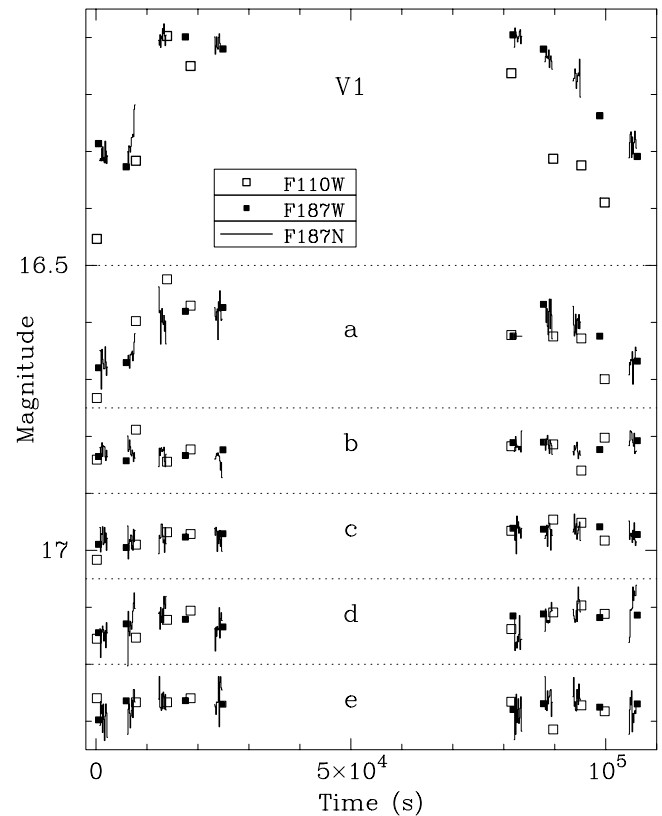


FIG. 6.—Time series for V1 plus five near neighbors. The open squares show the F110W data (averaged over each orbit), the filled squares, the F187W data (orbital average), and the solid lines, the F187N data. For V1, the zero points have been adjusted so that the F187W and F187N filters have the same magnitude for orbit 3 as F110W. For the neighboring stars, the zero points have been adjusted so that the average magnitude of the three filters over all of the orbits are equal. A further correction was applied to offset the time series from each other.

Besides the overlapping star *a*, V1 clearly stands out from its near neighbors. A distinctive element of the light curve of V1 is its asymmetry, typical behavior for RR Lyraes of type *ab*. Motivated by this, we carried out fits of our NICMOS light curves to two sets of IR light curves for RR Lyraes,  $K$ -band templates from Jones, Carney, & Fulbright (1996), and the  $JHK$  light curves of Cacciari, Clementini, & Fernley (1992) for three field RRab Lyraes. We varied the period, magnitude zero point, and amplitude of the IR light curves (tabulated as functions of phase) to minimize the residual between our light curves and the tabulated light curves. Since the F187W and F187N filters lie roughly halfway between the ground-based  $H$  and  $K$  passbands, we used both  $H$  and  $K$  data to fit to our combined long-wavelength (F187W and F187N) light curves. We used  $J$  data to fit to our F110W light curves.

Jones et al. (1996) give templates for (1) RRc variables, (2) RRab variables,  $A(B) < 1.0$  mag, (3) RRab stars,  $1.2 < A(B) < 1.3$ , (4) RRab stars,  $A(B) \approx 1.5$  mag, and (5) RRab stars,  $1.6 < A(B) < 1.7$ . By examining the residuals and comparing them with the expected scatter we can reject template (1) at the  $\sim 3.3 \sigma$  level (the derived amplitude of 0.21 mag is also too high by about a factor of 2). The best fits were obtained for the (3), (4), and (5) templates, with little difference among these three. With (4) for example, we derived a period of 0.60 days and a peak-to-peak amplitude of 0.25 mag when fitting to the  $1.87 \mu\text{m}$  filters.

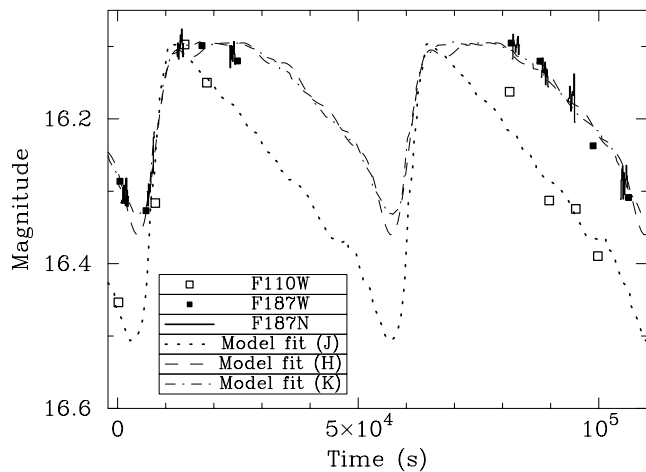


FIG. 7.—Time series for the RR Lyrae variable (V1). The open squares show the F110W data, the filled squares, the F187W data, and the solid lines, the F187N data. The fitted  $J$ ,  $H$ , and  $K$  templates are shown by the dotted, dashed, and dot-dashed lines, respectively.

The Cacciari et al. (1992) light curves for W Tuc gave the best fit to our data. For  $J$ , we derived a period of 0.63 days and an amplitude of 0.44 mag when fitting to F110W. Using  $H$  and  $K$  time series when fitting to the  $1.87 \mu\text{m}$  filters, we derived periods (amplitudes) of 0.61 days (0.24 mag) and 0.61 days (0.25 mag), respectively. The ratio between the amplitudes derived for  $J$  and for  $K$  was only 15% larger than the ratio for the field systems, a reasonable agreement given the differences between the *HST* and ground-based filters. The similarity between the derived periods shows that the error for the period determination is likely to be only 5%–10%. The rms values of the residuals from these fits are 0.018 (Jones  $K$ ), 0.021 (Cacciari  $J$ ), 0.017 (Cacciari  $H$ ), and 0.016 (Cacciari  $K$ ), consistent with the noise properties of stars in a similar magnitude range (see Fig. 1).

Figure 7 shows the results of these fits. Note the similarity between the  $H$ - and  $K$ -band template light curves, the close correspondence between the F187W and F187N data, and the rapid rise time for the F187N data near 7000 s (matching well with the template light curves).

### 3.3. A Search for Blue Variables: V2

Along with the general search for variables in the NIC2 images, we also paid special attention to stars with blue colors in an attempt to find the infrared counterpart to the LMXB known in Terzan 5 and to search for other RR Lyrae variables and possible bright BS variables.

To select a robust sample of stars for time-series analysis, only the stars with  $\text{CL} < 1.5$  in the F187W image were examined in greater detail. To compare our photometry with that of Cohn et al. (2000), we show in Figure 8a the F110W versus F110W – F187W CMD and in Figure 8b the F187W versus F187N – F187W CMD based on the flux values derived from our time series. The labeled stars from Figure 5 are shown plus extra stars with apparently blue colors from our photometry (labeled with a plus sign). Note that (1) the RR Lyrae variable is found in a similar part of the F110W versus F110W – F187W CMD as in Figure 5, (2) many of the blue stars labeled with an asterisk from Figure 5 are missing from Figure 8 because they are too contaminated, and (3) of the blue stars that do appear, most

of them, reassuringly, have blue colors. Apparent Paa-bright objects in Figure 8b are caused by errors from near neighbors.

Figure 9 shows the corresponding plots of rms versus magnitude. Using an uncontaminated sample of stars causes a significant reduction in the number of false variables appearing in these plots. In particular, the RR Lyrae variable and its near neighbor stand out much more clearly from the other stars. The star labeled with “V2” also has an unusually large rms, especially in the F110W filter. This large rms is unlikely to be caused by near-neighbor effects, since this star is well isolated from other stars, having  $\text{CL} = 0.05, 0.24,$  and  $0.22$  in F110W, F187W, and F187N, respectively. (The dithered images show a faint star about 2 pixels away from V2 that is too faint to be included in the master star list. However, this star makes less than 10% contribution to the counts in V2’s aperture.) Also, there are no bad pixels or other obvious artifacts near this star. Figure 10 shows plots of the time series for V2.

The absolute magnitude of V2 is uncertain because we lack optical information for this star and only have limited color information. Noting that V2 lies near the end of our BS sequence in Figure 5, we assume that an 8000 K Kurucz atmosphere gives a reasonable approximation to the spectrum of V2 and thus estimate that  $M_V \sim 2.0$ .

Power spectrum analysis gave periods and amplitudes of 6.94 hr and 0.27 mag (F110W), 6.93 hr and 0.33 mag (F187W), and 6.88 hr and 0.27 mag (F187N), assuming the variation is sinusoidal. By adapting the fitting technique used for the RR Lyrae variable (using a sinusoid for the template), we estimated the periods and amplitudes to be  $6.96 \pm 0.20$  hr and  $0.27 \pm 0.09$  mag (F110W),  $6.74 \pm 0.25$  hr and  $0.40 \pm 0.19$  mag (F187W), and  $6.85 \pm 0.6$  hr and  $0.29 \pm 0.27$  mag (F187N), respectively, in good agreement with the power spectrum results quoted above. Using this fitting procedure, the rms values of the residuals were found to be 0.045, 0.062, and 0.122 mag for the three filters. These values agree well with the mean rms values ( $0.045 \pm 0.010$ ,  $0.069 \pm 0.026$ , and  $0.111 \pm 0.032$ ) determined for the bins containing V2 in Figure 9. While a slightly larger amplitude is suggested for F187W, the errors for this filter are quite large, and a single sinusoidal fit to all of the data is allowed by the errors. For example, adopting a “compromise” solution for all three filters of period 6.98 hr and amplitude 0.282 mag gives rms residuals of only 0.049, 0.075, and 0.126 mag, comfortably within the  $1 \sigma$  limits quoted above.

## 3.4. Millisecond Pulsar

### 3.4.1. Astrometry

The position of the MSP in Terzan 5 is known to within  $0'08$  (Fruchter & Goss 2000) in the radio frame of reference (which uses quasars), but positional information given in the NICMOS data files is accurate to only about  $1''$  in absolute terms and is limited by uncertainties in the locations of the instrument apertures relative to the Optical Telescope assembly axis and the inherent uncertainty in the positions of the two guide stars used. For *HST* images, differential astrometry (measuring relative positions within an image) is much more accurate. We therefore carried out an astrometric study of the Terzan 5 field to improve the absolute accuracy of the positions and cut down the size of the error circle for the MSP. Our positions should then only be limited by uncertainties in our astrometric solution and

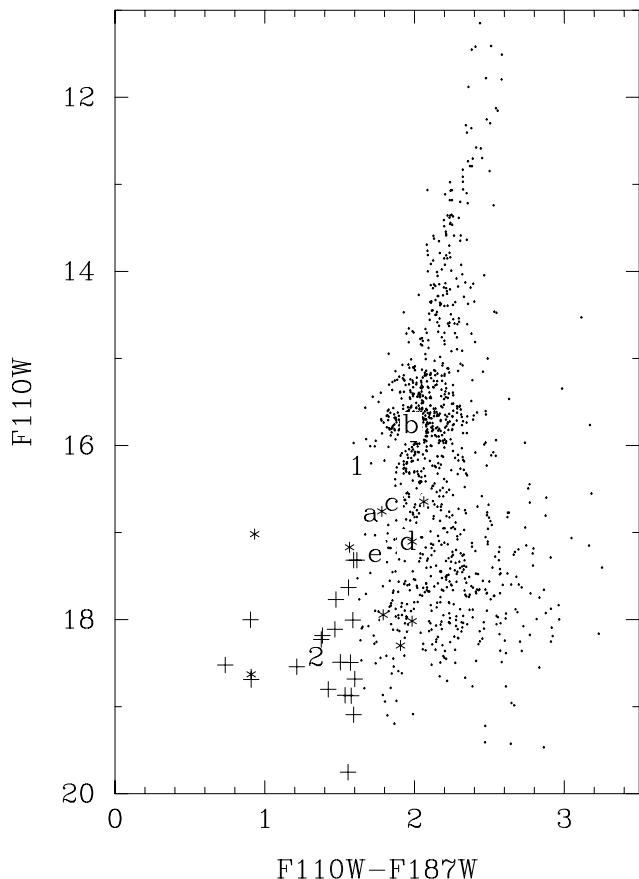


FIG. 8a

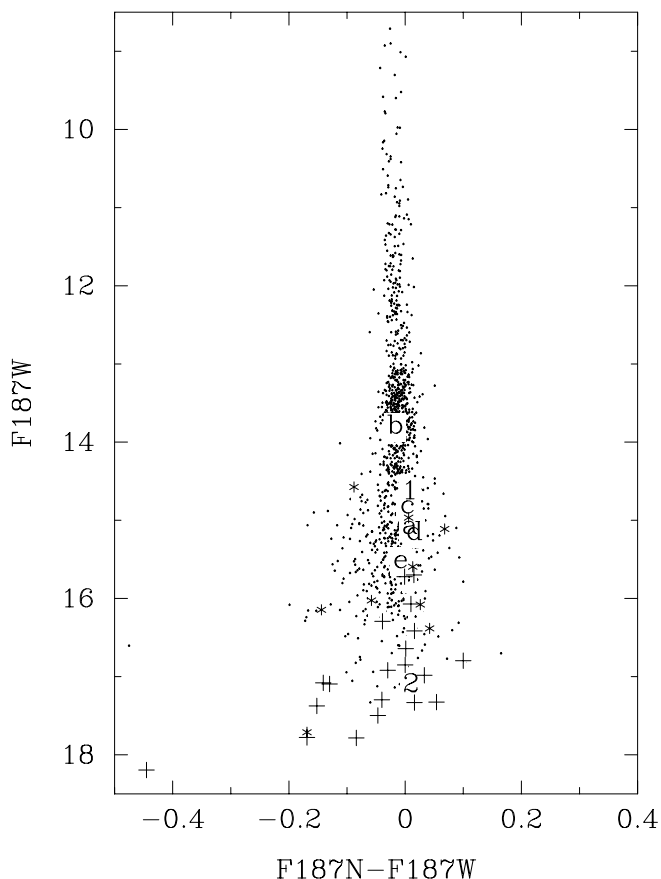


FIG. 8b

FIG. 8.—CMDs from combining the time-series photometry. Fig. 8a shows the F110W vs. F110W – F187W CMD, and Fig. 8b shows the F187W vs. F187N – F187W CMD. Only stars with CL < 1.5 in F187W have been plotted here. The numbered and labeled stars from Fig. 5 are shown along with extra blue stars from our photometry (*plus signs*).

by systematic errors in the STScI Digitized Sky Survey (DSS).

We used two steps to carry out this astrometric study: (1) We matched up the maximum possible number of stars (nine) between the DSS and the study of Ortolani et al. (1996) and used a linear regression in  $x$  and  $y$  to calculate an astrometric solution for the Ortolani stars. (2) We then performed a plate solution match between the Ortolani and NICMOS fields. A direct solution between the DSS image and the NICMOS fields was not possible because the small FOV of NICMOS and poor resolution of the DSS images limited the number of matching stars.

The position of the MSP is  $\alpha(2000) = 17^{\text{h}}48^{\text{m}}02^{\text{s}}.21$ ,  $\delta(2000) = -24^{\circ}46'37''.2$  (Fruchter & Goss 2000). Using the two steps described above, the nominal MSP position corresponds to pixel coordinates of 141.6, 180.5 for orbits 1–4, only  $0''.12$  from the predicted position using the header information. The rms residuals after applying the fit described in step (1) above are  $0''.341$  and  $0''.140$  in the  $x$ - and  $y$ -directions, respectively. The errors for step (2) are much smaller.

### 3.4.2. Photometry

Nice & Thorsett (1992) estimate that if the MSP companion is a main-sequence star, it is likely that  $0.09 M_{\odot} \lesssim M_2 \lesssim 0.11 M_{\odot}$ , right near the lower limiting mass for hydrogen burning. However, by analogy with the eclipsing MSP 1957+20, the optical counterpart is expected to be

much brighter ( $M_V \sim 10$ – $11$ ) than a normal main-sequence star because of reprocessing of pulsar spin-down energy on the evaporating wind. A search for photometric variability from the MSP nevertheless is very challenging given the considerable distance of the Terzan 5 MSP and its high reddening. These problems were compounded by three extra problems: (1) We had initially planned to observe the cluster center and the MSP simultaneously using the NIC1 and NIC2 cameras, respectively, in parallel, given the virtually identical value for the cluster center–MSP offset and the NIC1–NIC2 offset. However, in phase 2 planning we found that we were unable to use the required telescope roll angle and therefore decided to slew between the two targets, concentrating most of our time on cluster center and cutting our observing time on the MSP by a factor of  $\sim 4$ . This strategy effectively reduced the observed amplitude of any MSP variations that may be present. (2) The nominal position of the MSP lies close to a HB star and two bright giants (at relative distances of  $0''.55$ ,  $1''.3$ , and  $2''.5$ ; see Fig. 11). The extra background from the PSF halos of these bright stars compromised the MSP observations. (3) The NIC1 data are much more affected by transient artifacts, including “persistence,” than the central NIC2 data.

Despite these limitations, the MSP field data are less crowded than the central NIC2 data, enabling variability studies of stars at and below the MSTO. Our photometric analysis was similar to that carried out for the central NIC2 field except that we did not have the advantage of cross-



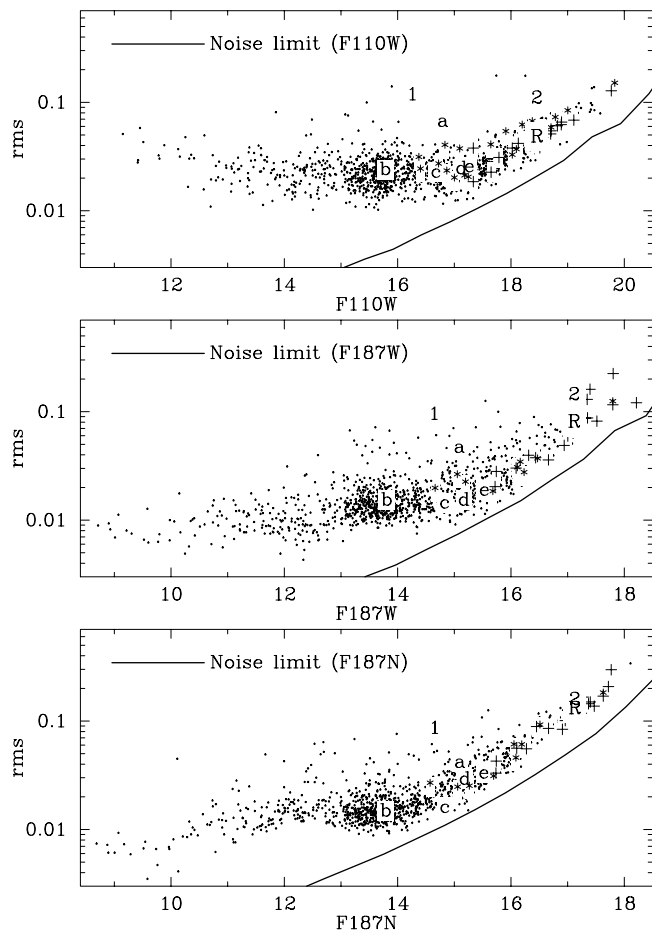


FIG. 9.—Similar plot to Fig. 1 except that only stars with CL (F187W) < 1.5 have been plotted. The variable V2 has been added to this figure, along with a symbol “R” showing the residual after subtracting a sinusoidal fit to the V2 light curve.

checking candidate variables between different filters. A plot of time-series rms versus magnitude for the MSP field is shown in Figure 12. The HB stars identified from the  $V$  versus  $V-I$  CMD of Ortolani et al. (1996) are labeled, as are stars (and in some cases PSF tendrils) lying within  $1''$  of the nominal MSP position and the two giants near the position of the MSP. Note that the stars near the MSP have slightly higher noise levels than average because of the higher background near the bright giant stars.

We carefully examined the results to search for evidence of variability, but no authentic variable candidates were found. We also carried out a second dedicated search for variability from the MSP by searching a grid of positions within a  $3\sigma$  ( $1''.1$ ) radius circle around the measured position of the MSP. Two criteria were used in this variability search: excess rms in a small group of adjacent pixels and high linear correlation of the eight-point time series with the predicted time series of the MSP (assuming a sinusoidal shape for the light curve and using the ephemeris of Nice & Thorsett 1992). No candidates for a variable MSP were found.

To estimate the depth of our MSP variability search, we used our Kurucz atmosphere/SYNPHOT simulations described above. We simulated MSP variations using sinusoidal light curves (at the MSP period of 1.82 hr) with an amplitude of 1 mag and added these light curves to our

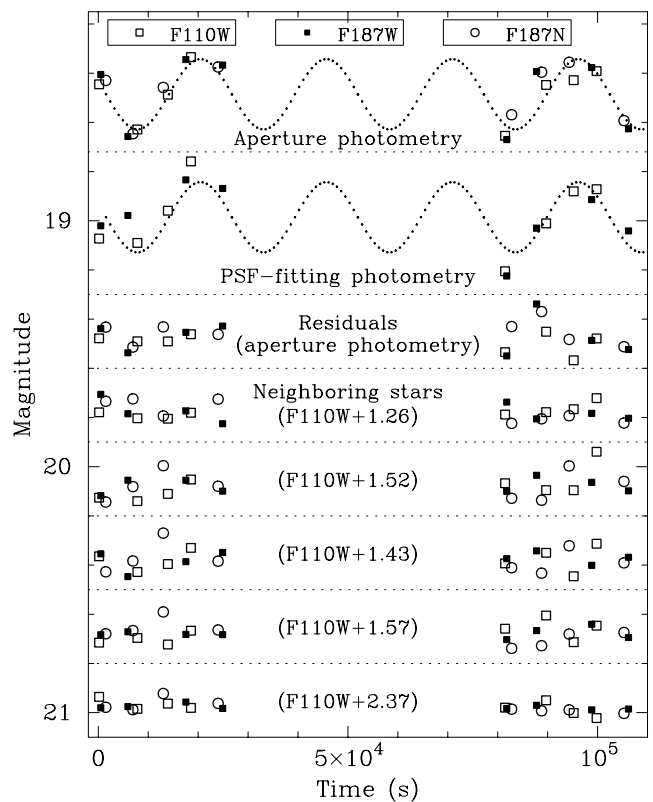


FIG. 10.—Light curves for V2. The upper panel shows the aperture photometry results (including a sinusoidal model fit to the data), the next panel the noisier PSF-fitting results, then the residuals after subtracting the model. The other panels show the light curves of five nearby stars, with the required F110W offset shown in parentheses.

measured light curves for the above grid. An MSP simulation was considered “detected” if the linear correlation between the predicted and simulated light curves was greater than 0.5 and the rms of the simulated light curve

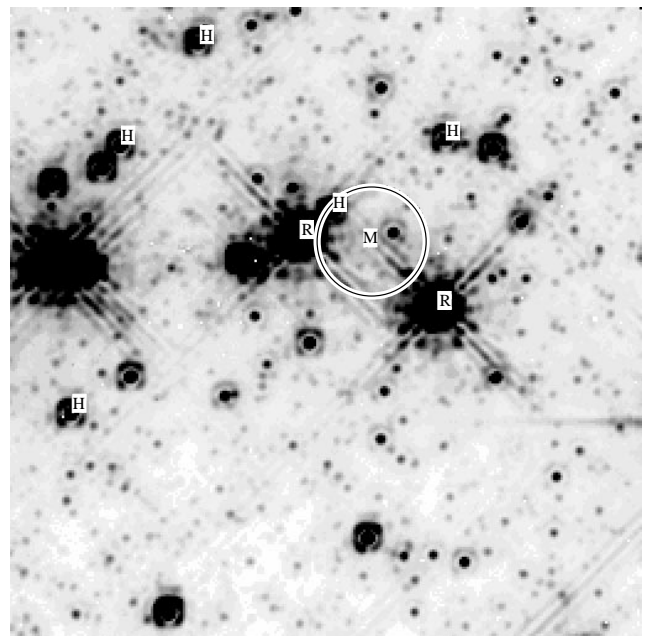


FIG. 11.—Finding chart for the NIC1 MSP field. The nominal MSP position is shown (M), along with HBs (H), and red giant stars (R) discussed in the text. A  $1''$  circle is plotted around the nominal MSP position.

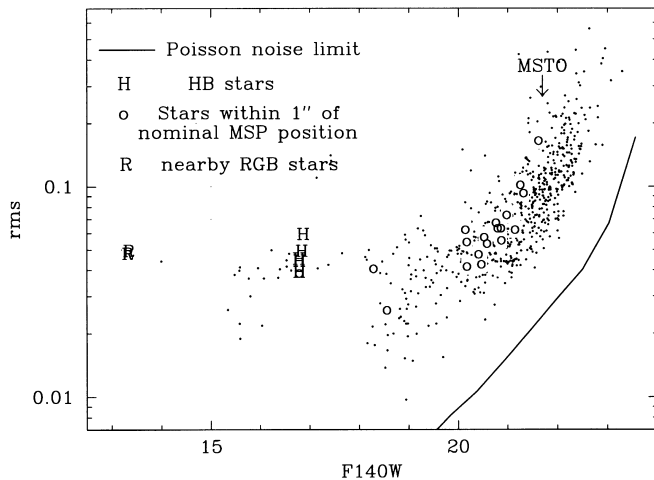


FIG. 12.—Plot of rms vs. magnitude for the NIC1 field containing the MSP. Stars within 1'' of the nominal MSP position are shown along with HB stars and red giant stars discussed in the text. The estimated position of the turnoff is shown.

was 50% higher than the original rms. At  $M_V = 3.9$  ( $F140W = 21.3$ ) only 43% of the simulations were detected and at  $M_V = 3.4$  ( $F140W = 20.0$ ) 86% of the simulations were detected. To show the effect of the high sky levels near the expected position of the MSP, we carried out another set of simulations for a grid centered on a point well away from the bright giants. Here our variability search was able to go 1.5 mag deeper but still falls well short of the desired levels to detect variability, assuming that the secondary has  $M_V \sim 10$ –11.

#### 4. DISCUSSION

##### 4.1. RR Lyrae Variable

The identification of V1 as a RR Lyrae variable and a cluster member is secure, based on the light curve, the position of the star in the CMD, and the small chance of field-star contamination. As with 47 Tuc, only one RR Lyrae has been discovered in Terzan 5, and the bulk of the HB stars are red and lie near the giant branch (see Fig. 5), as they do in most metal-rich globular clusters. However, Cohn et al. (2000) report the possible detection of a small number of blue HB stars in Terzan 5. The high reddening and crowding in this cluster makes such detections much more difficult than in NGC 6388 and NGC 6441, where many blue HB stars have been found and there are multiple RR Lyrae variables. Rich et al. (1997) have explored two possibilities to explain the blue HB star populations in NGC 6388 and NGC 6441, the effects of age and dynamics. At high metallicity an increase in age can populate a blue HB tail with stars at the low end of the mass distribution, while dynamical encounters in the cores of dense clusters can result in extra mass loss via tidal stripping. Rich et al. (1997) conclude that although neither effect alone appears sufficient to explain the cluster blue HBs, a combination of them may have an effect.

Our discovery of an RR Lyrae variable in Terzan 5 is therefore useful for the study of the influence of metallicity, age, and interaction rate on the production of HB stars in the instability strip. For example, Terzan 5 has a higher metallicity than any of the above clusters, which should result in fewer RR Lyraes, but it also has a higher inter-

action rate, which may result in a higher number of RR Lyraes (see Rich et al. 1997). It is possible that these two factors combine. For example, maybe a large number of stars in Terzan 5 lose mass via tidal stripping, but the cluster metallicity is high enough that only the stars with the most extreme mass loss show up as RR Lyraes.

Sweigart & Catelan (1998) note that the HBs in NGC 6388 and NGC 6441 have a pronounced upward slope with decreasing  $B-V$ , a result that is not predicted by canonical HB models and that cannot be reproduced by either a greater cluster age or enhanced mass loss along the red giant branch. They explore three possibilities to explain these sloped HBs: (1) a high helium abundance, (2) a rotation scenario in which internal rotation during the RGB phase increases the HB core mass, and (3) a helium-mixing scenario in which deep mixing on the RGB enhances the envelope helium abundance.

One prediction of the high- $Y$  scenario is that the number ratio  $R$  of HB stars to RGB stars brighter than the mean RR Lyrae luminosity should be large. We calculated  $R$  for Terzan 5 by defining the HB as those stars having  $15.6 < F110W < 16.1$  and correcting for the large number of RGB stars found in this region of the CMD by averaging and subtracting the number of stars present in adjacent magnitude bins ( $15.1 < F110W < 15.6$  and  $16.1 < F110W < 16.6$ ). Our value for  $R$  is  $1.03 \pm 0.11$ , where the error is based on Poisson statistics alone. Although systematics will increase the error, this value is clearly inconsistent with the high- $Y$  scenarios presented in Sweigart & Catelan (1998), where  $R = 3$ –4. Layden et al. (1999) came to a similar conclusion for their study of NGC 6441. Sweigart & Catelan (1998) suggest a variety of other observational tests for discriminating among the various scenarios, all requiring further observations.

Figure 5 shows that V1 may be somewhat brighter ( $\sim 0.3$  mag) than expected for a blue HB star, consistent with the sloped HB slopes mentioned above, although uncertainties in the large reddening for this cluster and the limitations of our simple HB model make detailed comparisons difficult. As Sweigart & Catelan (1998) point out, unusually bright RR Lyraes should have unusually long periods, as observed for the RR Lyraes in NGC 6388, NGC 6441, and 47 Tuc. This self-consistency between the RR Lyrae luminosities and periods is reassuring.

The obvious question arises: Is the period of V1 unusually long? First, the metallicity has to be considered. V1 is likely to be the most metal-rich RR Lyrae yet found in a globular cluster, since Terzan 5 is thought to have roughly solar metallicity (Ortolani et al. 1996) or even higher (Cohn et al. 2000 estimate  $Fe/H = 0.25$ ). NGC 6388, NGC 6441, and 47 Tuc have  $Fe/H$  values of  $-0.60$ ,  $-0.53$ , and  $-0.76$ , respectively.<sup>2</sup> It may even be the highest metallicity RR Lyrae ever found.

Examination of the metallicity-period relationship for field RR Lyraes (Layden 1995) shows that V1 has a significantly longer period than field stars with similar metallicity. The period-metallicity distribution of Pritzl et al. (2000) shows that V1 lies well outside the two Oosterhoff classes, with a longer than expected period given the metallicity of

<sup>2</sup>  $Fe/H$  values taken from the Catalog of Parameters for Milky Way Globular Clusters, compiled by W. E. Harris, McMaster University, revised 1999 June 22, available at <http://physun.mcmaster.ca/~harris/mwgc.dat>.

Terzan 5. Therefore V1 joins the rapidly growing subclass (suggested by Layden et al. 1999) of long-period RR Lyraes in metal rich globular clusters.

Also plotted on Figure 1 of Pritzl et al. (2000) are the periods and metallicities of the RR Lyraes in NGC 6388 and NGC 6441. These two clusters are clearly separate from the two Oosterhoff classes, with higher metallicity and longer periods. Interestingly, while the average period for these two clusters is longer than *all* of the Oo I and Oo II globulars, V1 has a period lying almost exactly between the two Oosterhoff groups. Further, a line drawn between V1 and the average of NGC 6388 and NGC 6441 in the period-metallicity plot lies almost parallel to the line between the two Oosterhoff classes, suggesting two period-metallicity relations with similar slope may exist.

This interesting but speculative result clearly requires verification by observing a larger sample of RR Lyraes in clusters with solar metallicity or above. It could be that V1 has an unusually short period compared to other (undetected) RR Lyraes in this cluster. For example, the periods in NGC 6441 alone range from  $\sim 0.6$  to  $\sim 0.9$  days, with a reasonably flat distribution between these two extremes.

#### 4.2. The Faint Variable V2: LMXB or Eclipsing BS?

To summarize our results, V2 is blue, relatively faint, and variable, with a near sinusoidal light curve and a period of  $\sim 7$  hr. We consider two possibilities for this variable, that it is an LMXB or that it is an eclipsing BS.

First, we consider the LMXB hypothesis. In this case the variability could be caused by at least three different phenomena:

1. Ellipsoidal variations from distortion of the secondary. These variations typically have a distinctive double-lobed pattern, with a difference in depth between successive minima of  $\sim 0.05$ – $0.10$  mag and an expected difference in amplitude between F110W and F187W of  $\sim 0.05$  mag, using reasonable assumptions regarding mass ratios, temperatures, and inclinations (W. van Hamme 2000, private communication). These amplitude differences are not clearly detected in the data, though the relatively large error for the F187W amplitude means that we cannot rule out this possibility.

2. Another possible explanation of variability, under the LMXB hypothesis, is the effects of heating of the secondary by the disk and neutron star. Here the expected light curve is also double-lobed, but with the positions of the deep and shallow minima reversed (see van Paradijs & McClintock 1995). A large contribution from heating would be obvious in the light curve because of the significant expected difference in eclipse depth, but a small contribution would plausibly cancel out the difference between the depths of adjacent minima when combined with an ellipsoidal variation. However, this requires some fine-tuning of the binary parameters, and a difference between the light-curve amplitudes remains (W. Van Hamme 2000, private communication).

Note that if either case (1) or (2) applies to V2, then the period would be twice the 7 hr sinusoidal variability period, i.e.,  $\sim 14$  hr. It would thus be similar to the field LMXB and recurrent transient Aql X-1 (Chevalier & Ilovaisky 1991), an attractive possibility given the transient, or highly variable nature, of the Terzan 5 LMXB.

3. Flickering from the disk may also be expected to show up in the light curve of an LMXB, as it does in field systems. If V2 is an LMXB, the blue color of V2 would imply a reasonably prominent disk (the source of flickering). However, no evidence for flickering is seen as the residuals after subtracting the sinusoidal model are consistent with the noise properties of the data.

Besides being blue, variable objects, LMXBs also typically have weak emission lines in the optical and infrared. Shahbaz et al. (1996) show that the average  $H\beta$  EW of 15 LMXBs is  $1.9 \text{ \AA}$ . Scaling by the average EW ratio between  $H\beta$  and  $P\alpha$  for the two CVs PQ Gem and EX Hya (using values from Dhillon et al. 1997; no published  $P\alpha$  EWs for LMXBs were found) we expect an average  $P\alpha$  EW of  $3.8 \text{ \AA}$ . This is equivalent to  $F187N - F187W = -0.07$ , well below the  $1 \sigma$  error for the faint end of our F187N versus F187W CMD (containing V2) of  $0.11$  mag. Therefore the  $P\alpha$  data are inconclusive in determining whether V2 is an LMXB.

An obvious constraint on the identity of V2 is its position relative to the X-ray source identified by Johnston et al. (1995). Our measured positional offset of  $5''.5$  is just outside the  $5''$  error circle quoted by Johnston et al. (1995). We hope to reduce significantly the size of this error circle with the use of our Cycle 1 *Chandra* observations. With these deep, 50 ks observations, the LMXB should have an error circle less than  $1''$  and should be distinguishable from the large expected population of CVs and MSPs in this cluster unless it is in deep quiescence.

We may also compare the period and luminosity of V2 with UV or optically identified globular-cluster LMXBs. Three of the six globular-cluster LMXBs with optical counterparts have  $M_V \gtrsim 4.5$ , according to Deutsch, Margon, & Anderson (2000). Figure 4 shows that this is beyond our detection limits for stars on the main sequence or the giant branch (for hotter objects our detection limits are even shallower). To make matters worse, the Terzan 5 LMXB, being a transient, should be fainter than most other cluster LMXBs. We can predict  $M_V$  using the dependence of optical luminosity on X-ray luminosity and period (van Paradijs & McClintock 1994), a relation that holds for both cluster and field systems as shown by Deutsch et al. (2000). For a period of  $\sim 14$  hr, we estimate  $M_V = 4.2$ , beyond our detection limits. Finally, we note that four of the five systems with optical counterparts and measured periods have period  $\lesssim 5.7$  hr, and three have periods  $\lesssim 0.73$  hr.

To summarize, although we find no *individual* argument gives compelling evidence against V2 being the infrared counterpart of the Terzan 5 LMXB, the accumulated weight of evidence argues against it. An alternative hypothesis is that V2 is an eclipsing BS. This is consistent with (1) the position of V2 in the F110W versus F110W – F187W CMD (see Fig. 5). V2 has about the same luminosity as the brightest BS in 47 Tuc, and its luminosity may also be significantly enhanced by its binary companion. (2) The light-curve amplitudes of V2. Sinusoidal light curves with our measured amplitudes are easy to reproduce using the light-curve models of Wilson for W UMa systems (van Hamme 2000, private communication). A growing number of binary BSs are being discovered in globular clusters (e.g., Edmonds et al. 1996; Kaluzny et al. 1998), although the fraction of BSs that are binaries is typically quite low.

(3) The inferred orbital period of 14 hr is consistent with the periods of other binary BSs in globular clusters such as 47 Tuc (Edmonds et al. 1996). As with the LMXB hypothesis, the  $\text{Pa}\alpha$  data are inconclusive, since for a model BS with  $T_{\text{eff}} = 8000$  K (at the top of our artificial BS sequence),  $F187\text{N} - F187\text{W} = 0.04$ , well within our 0.11 mag scatter for this line discriminant.

Using our simulations we can ask how many eclipsing binaries we should expect to see with our data set. Since most eclipsing binaries discovered in clusters are found near the MSTO (e.g., Edmonds et al. 1996) and we have very little sensitivity to such variables, the simple answer is none. Therefore, a naive calculation may predict a very large number of eclipsing systems (and BSs) should be found in Terzan 5 if V2 is indeed an eclipsing BS. While clearly small number statistics apply since we have detected only one system, it is striking that evidence exists for a bright eclipsing BS at the edge of our detection limits. A relatively large number of BSs and binaries would have interesting consequences for the dynamics of this extreme globular cluster. For example, a high BS number may be caused by a high stellar interaction rate, which itself may be enhanced by a large binary fraction. A high interaction rate is expected for Terzan 5 because of its moderately sized core and extremely high stellar density (Cohn et al. 2000). Terzan 5 also may be the globular cluster with the largest population of MSPs in the galaxy (Fruchter & Goss 2000), further evidence for possible large interaction rates.

It is useful to discuss the potential for detailed studies of other interaction products or binaries in Terzan 5. Our upcoming GO *Chandra* observations of Terzan 5 should allow a deep search for CVs in this cluster unless the LMXB is in outburst. Unfortunately, optical or IR identifications of such sources will be extremely difficult or impossible. We have already seen the problems with IR observations where crowding prevented us from reaching even close to the MSTO, but with their smaller PSFs, *Gemini* and the *Next Generation Space Telescope* will offer substantial improvements over *HST* for studying this cluster. In optical passbands such as *V* the PSF will be substantially reduced in size, but the enormous reddening for this cluster implies that the MSTO will be found near  $V \sim 25.5$  and therefore CVs at  $V \gtrsim 28$ . Studies of the BS sequence will be difficult but may be feasible depending on the results of detailed crowding simulations.

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